

MIXING PHYSICAL HABITAT AND STREAMFLOW TIME SERIES ANALYSIS

Robert T Milhous¹

Corresponding Author: Robert Milhous, robert_milhous@usgs.gov

Abstract

Four observations from two case studies are presented: physical habitat analysis of the Virgin River in southwestern Utah and upper Animas Basin in southwestern Colorado. The Virgin River is usually considered a sand bed river. Cross-sectional measurements, made at three streamflows, show there was considerable change in the channel between the times of the three sets of measurements. First observation: important to keep the three sets of data as individual data sets. Second observation: the channel index is not fixed in a river with a moveable-bed and changes affect understanding of the aquatic system. The Animas River has a wide range of streamflows and high metals toxicity. Both winter and spring discharges may limit trout populations. Third observation: (from Animas River) habitat time series analysis should be done with a model that specifically links physical habitat relations and streamflows. Fourth observation: annual time series of habitat suitability considering metals toxicity can be generated. Considering the third and fourth observation together leads to the secondary observation that the hydraulic and stream flow conditions that favor one species may not be as good for the species favored by the water quality conditions.

Introduction

Four "observations" from two case studies of physical habitat analysis are presents in this paper. The central theme is that considerable knowledge about the aquatic environment is gained by the development of an understanding of how the physical habitat changes with time (time series simulation). The two case studies are the Virgin River in southwestern Utah, and the Animas River in southwestern Colorado. The Virgin River case study illustrates two of the four observations: 1) the importance of separate analysis of data sets obtained at different times when a river channel changes with time, and 2) that there can be important changes in the substrate with time. In some ways there is only the first observation (analysis of physical habitat as a result of changes in the channel) but changes in the substrate are important enough that they are being presented as a separate observation. There are two additional observations from the Animas River case study. The first is that time series analysis can be used to investigate the importance of the annual extremes of streamflows (spring runoff – high streamflow, and winter base flow – low streamflow) to the quality of the physical habitat. The second observation is that a time series of habitat suitability can be developed that includes the impact of metals concentrations on the overall suitability.

This paper illustrates the process of developing habitat time series by presenting a series of graphs. The goal is to show how to develop time series of

¹ Fort Collins Science Centre, US Geological Survey. 2150 Centre Avenue, Building C. Fort Collins, Colorado 80526. email: robert_milhous@usgs.gov.

importance to the analysis of physical habitat for aquatic animals. The paper does not justify any of the analytical paths illustrated in the paper. The paper is a 'way station' in the process of attempting to improve environmental flow analysis with an end goal of making an improvement to techniques for linking streamflow, physical habitat simulation, and a habitat quality index as represented by the Index of Biotic Integrity (Karr, 1991).

An assumption made in writing this paper is that the reader has a working knowledge of the Physical Habitat Simulation System (PHABSIM); and at least some knowledge of habitat time series analysis within the context of the Instream Flow Incremental Method (IFIM). The four 'observations' are standalone and are not linked except in the discussion. The reader should obtain some insight into how improve the use of time series analysis using habitat simulation from each of the four observations.

Virgin River Case Study

The Virgin River is a mostly sand bed river. The study area is located in Washington County Utah and in adjacent Arizona and Nevada. Most of the study reaches are not stable in that the channel changes reasonably frequently. There are some stable reaches in the upper reaches of the river. Information for only one reach of the river is presented in this paper. The reach is in Little Round Valley near Hurricane, Utah.

Observation 1. Time series analysis in a moveable channel.

The physical habitat versus discharge relations for desert suckers larger than 90 mm in the Little Round Valley reach are presented in Figure 1. The relations were calculated using three different measured data sets and various programs in the Physical Habitat Simulation System (PHABSIM). The programs are described in Milhous et al (1989). In this paper monthly values of the streamflows on the Virgin River near Hurricane are being used in the time series analysis. The maximum monthly discharge during the period of record was 1657 cfs. The physical habitat relations were developed discharges between 12 and 1000 cfs and linear interpolation used for the 3% of monthly discharges larger than 1000 cfs. It was assumed the physical habitat at a discharge of zero was also zero

The relations in Figure 1 are composites of two relations calculated using different uses of the velocities to calibrate the PHABSIM hydraulic models. There is a significant concern that the measured velocities will not result in a good relation for discharge up to 1000 cfs. A procedure for dealing with this concern is to simulate the relations using hydraulic models in PHABSIM calibrated to depth only for the higher discharges. This was done and the weights used to merge the two relations (calibrated to velocity, calibrated to depth only) for the three sets of data are given in Table 1. For discharges less than the calibration discharge the velocity calibrated results were always used; for the two highest discharges (750 and 1000 cfs) the depth only calibration was used; and for intermediate discharges, judgment was used in selecting the weights. An example of how the relations are combined into a single relation is shown in Figure 2 for the middle discharge data set. The equation used to combine a relation calculated using a velocity-calibrated model with one with only depth calibration is:

$$HAC(i) = [HAV(i) * w(i)] + [HAD(i) * (1-w(i))]$$

where $HAV(i)$ is the habitat calculated using the velocity calibration, $HAD(i)$ the habitat calculated with depth calibration only, and $HAC(i)$ is the composite (or weighted) habitat. The weight on the habitat calculated using the velocity-calibrated model is $w(i)$. Both $w(i)$ and $(1-w(i))$ are given in Table 1.

The first approach to handling the three different relations in Figure 1 would be to assign a range of discharges to each of the three sets based on the discharges. But before that is done, the channel morphology data should be done. This is done by comparing cross sections, and the longitudinal profiles, for the three different data sets. The longitudinal profiles for the three data sets available for the Little Round Valley reach are presented in Figure 3. The working assumption behind the idea of using segments of each relation is that the channel deepens as the discharge increase and fills as the flow decreases; in addition it is assumed that the pattern repeats with each successive pattern of streamflows. Note that in Figure 3 this assumed pattern of a does not occur. The high discharge profile is mostly the highest level (except for the cross section at about 600 feet) the low discharge data set smoothed the cross section and filled the hole at about 600 feet.

The daily streamflows in the Virgin River at Hurricane during the period of the field measurements and just prior to the first measurement are presented in Figure 4. The smoothing of the profile probably occurred because the river had sufficient competence to move the substrate material (mostly sand) and continued to move the sand in the river without much sand being delivered to the main channel. Prior to the high discharge set of measurements the river almost certainly received large quantities of sediment from the tributaries. In Figure 3 the profile for the middle set of discharges shows the river has continued to remove sediment along the whole of the reach between the end of July 1993 and early March 1994.

An index to the ability of a river to transport sediment has been developed (Milhous, 1995). This index (Sediment Transport Capacity Index – STCI) was calculated for the gage with a long record further downstream than the Hurricane gage. The annual values of the STCI are presented in Figure 5.

The change in the channel is not a simple relation between the discharge and the channel shape (meaning the scour/fill of the cross section is related to discharge - filling as the flows decrease, scouring as the flow increases) but the channel shape is related to the past history of the streamflows and the sediment yield to the stream from the tributary watershed. The high flow channel probably represents the channel following major storms, and the middle set a common condition after the sediment (sand) has had time to move through the system, the low flow data set may represent the channel following the more common storms with reasonably high discharges but not storms (as in 1993) that may have move significant amounts of sand from the watershed to the channel. The change in the channel in 1993 was certainly related to the storms that occurred the winter before.

The time series of the three physical habitat versus discharge relations are given in Figure 6. Because the channel characteristics are not a simple relation with discharge, the three relations only give some idea of the physical habitat ranges that may have occurred over time.

Observation 2. Change in the substrate with time.

Figure 7 shows the change of the substrate with time. The change in the bed-material composition of the Little Round Valley reach of the Virgin River is indicated by the observed substrate index. The substrate index was a classification based on particle size. Note the loss of sand in the 222 days between the low and middle discharge measurements. The river is tending to return to a previous state as far as the composition of the substrate is concerned. Because the substrate suitability is the same (1.0) for all values of the substrate and for all fish and life stages the impact of the change in the substrate would be important only for the hydraulics - this could be important.

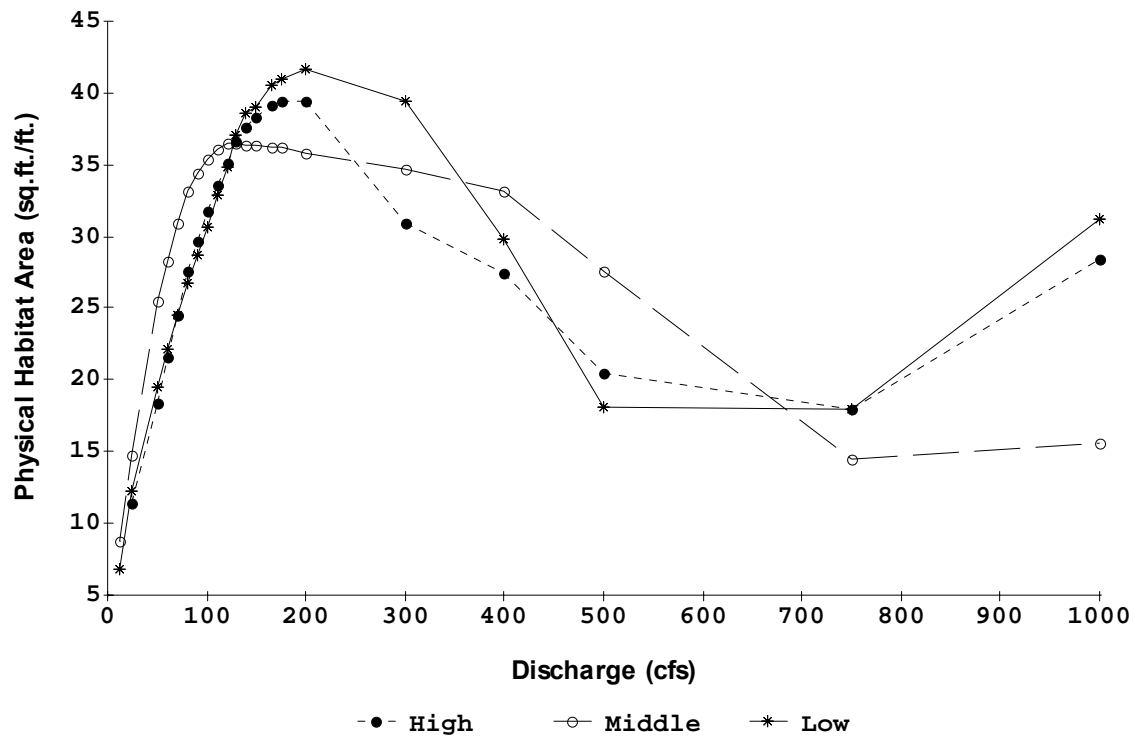


Figure 1. Physical habitat versus discharge relations for desert sucker (*Catostomus clarki*) in the Virgin River at Little Round Valley, Utah. The three sets of measurements used to calculate the relations were made on 10 June 93 (high flow data set - 387 cfs), 23 July 93 (low flow data set - 71 cfs), and 02 March 94 (middle flow data set - 278 cfs).

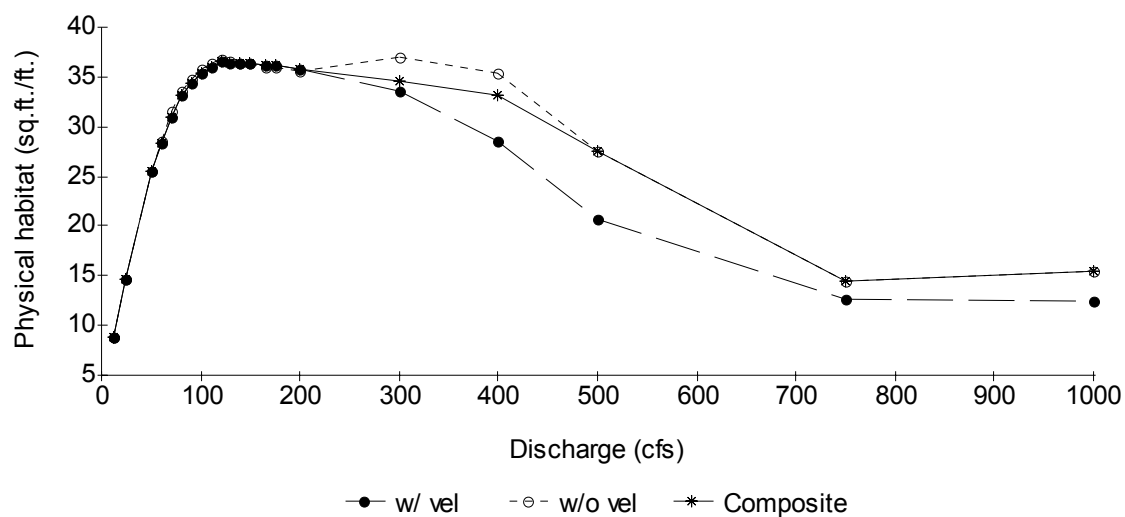


Figure 2. The physical habitat versus discharge relations for Desert Suckers larger than 90 mm in the Virgin River at Little Round Valley, Utah based on the middle set of discharge measurements.

Table 1. Weights on physical habitat calculated using models in PHABSIM calibrated to measured velocities. The weight on the physical habitat calibrated to variation in depth only. The dates and measured discharge for the three (high, low, and middle) measured data sets.

	High 10 June 93	Low 23 July 93	Middle 2 March 94
Discharge (cfs)	387	71	278
12	1	1	1
25	1	1	1
50	1	1	1
60	1	1	1
70	1	1	1
80	1	1	1
90	1	1	1
100	1	1	1
110	1	0.67	1
120	1	0.33	1
130	1	0	1
140	1	0	1
150	1	0	1
165	1	0	1
175	1	0	1
200	1	0	1
300	1	0	0.67
400	0.67	0	0.33
500	0.33	0	0
750	0	0	0
1000	0	0	0

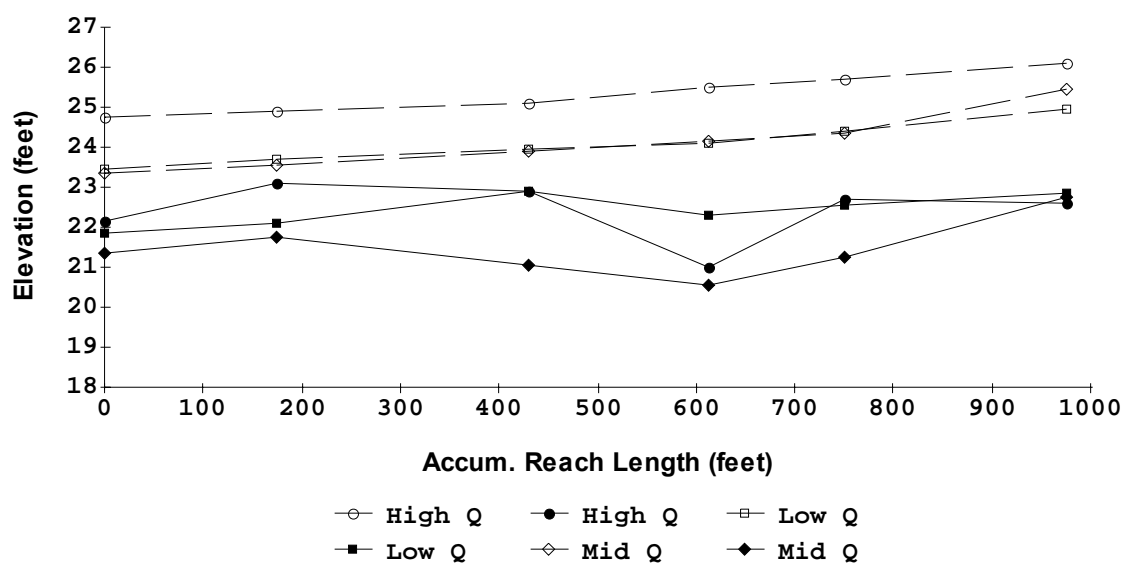


Figure 3. Longitudinal Profile of the Little Round Valley Reach of the Virgin River, Colorado for three sets of cross-sectional measurements.

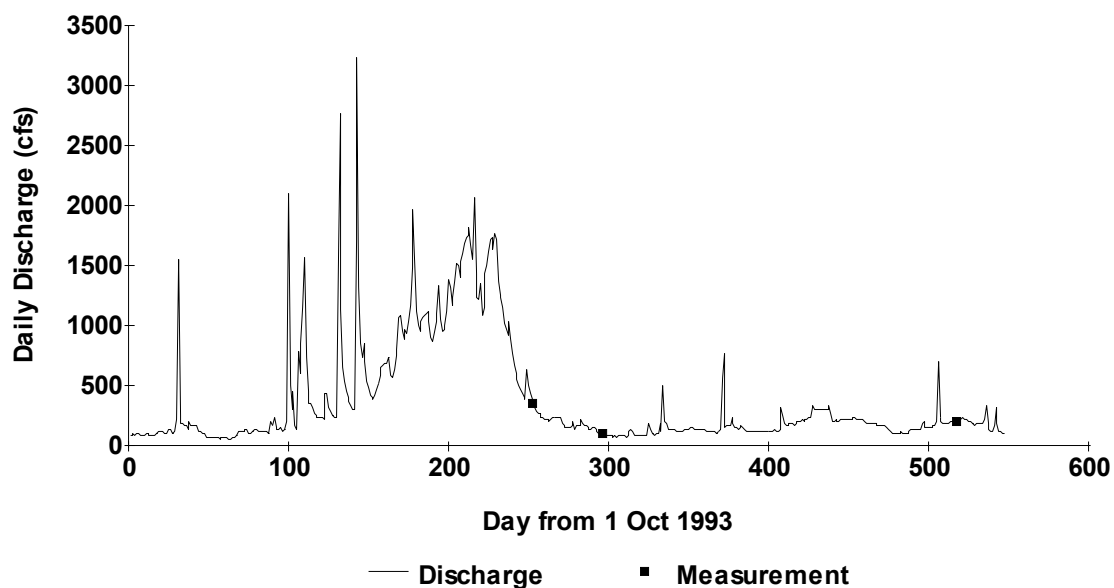


Figure 4. The daily discharges in the Virgin River near Hurricane, Utah from 1 October 1992 thru 31 March 1994 (547 days) are shown in this slide.

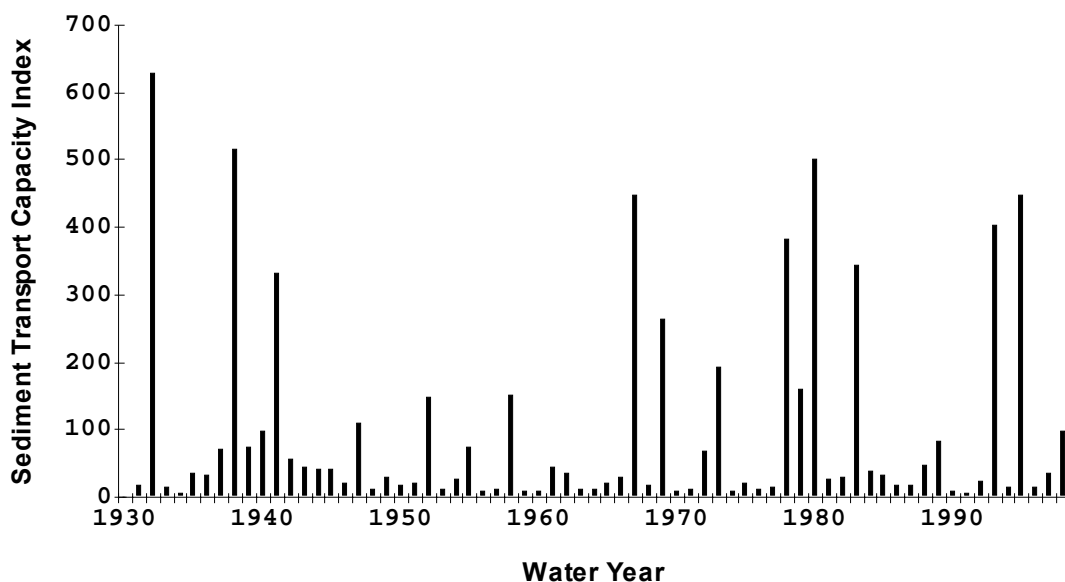


Figure 5. Sediment transport capacity index for the Littlefield, Arizona gage (Virgin River at Littlefield, AZ). A major dam-break flood occurred in 1989; if the STCI gives us information on the yield of sediment to the river then 1993 followed a period with small yield to the river. The 1989 flood probably modified the channel and the 1993 events could have caused a return to the old - except other sites on the Virgin River above the failure had a similar change.

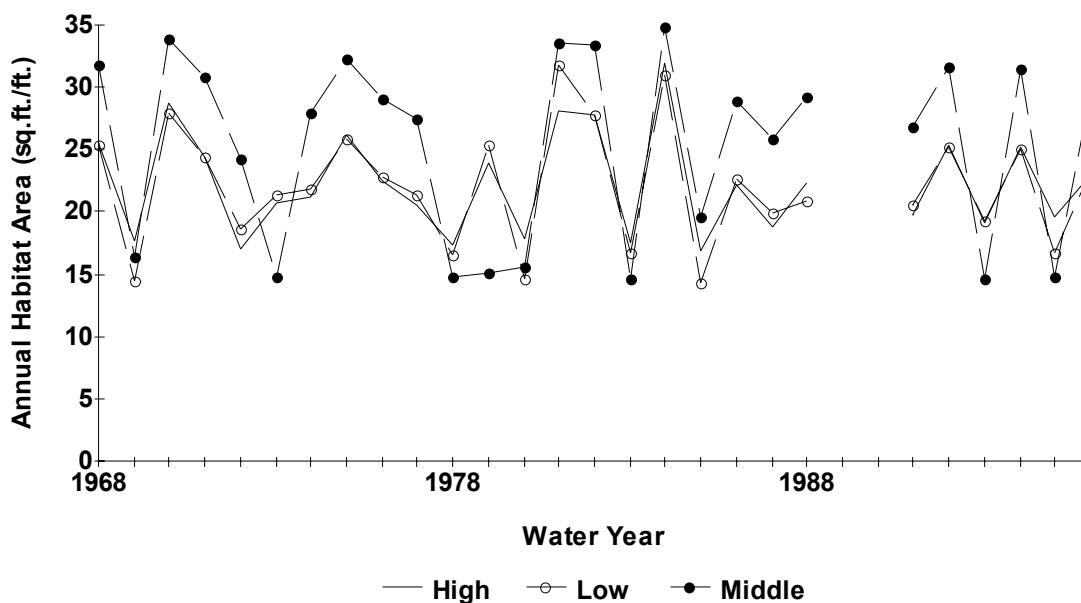


Figure 6. Three time series of the monthly habitats for desert suckers larger than 90 mm for the Little Round Valley reach of the Virgin River. Streamflows used in the simulation was the monthly discharges at the Hurricane gage on the Virgin River.

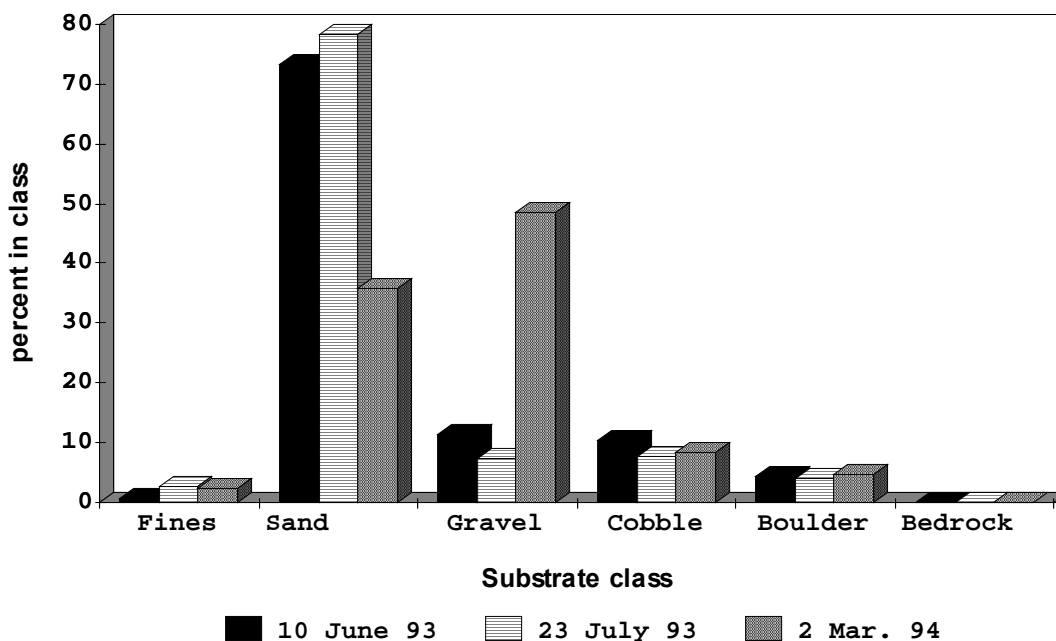


Figure 7. The change in the bed-material composition of the Little Round Valley Reach of the Virgin River as indicated by the observed substrate index.

Animas River Case Study

The Animas River is located in the San Juan Mountains and Colorado plateau of southwestern Colorado New Mexico and joins the San Juan River at Farmington, New Mexico. The native trout in the Animas Basin are cutthroat trout. Few native trout remain and the trout found in the upper watershed are brook trout with rainbow and brown trout in the lower river. There is considerable metals contamination in the upper basin near Silverton but a brook trout fishery does exist in the Animas River from just above Howardsville to where the Animas joins Cement Creek in Silverton (Milhous, 1999). The Upper Animas River watershed is in San Juan County, Colorado and is located in the San Juan Mountains. The lower river is in the Colorado Plateau country. The winters are cold with considerable snowfall and little snowmelt in the mountains in the upper part of the basin. The lower basin has less snow but the winters are still cold. The streamflows during the winter are low and reasonably stable in that the flows during the winter do not change significantly.

Observation 3. The simulation of time series for high and low streamflow conditions

The high flow condition in the Animas River considered in this paper is spring runoff; the low flow streamflow conditions are winter streamflow. The physical habitat as a function of discharge relations in the Animas River at Howardsville for trout and benthic invertebrates are presented in Figure 8. This analysis is based on discharge

measurements at the gage and calculated using the HABVD program in PHABSIM (Milhous et al, 1989). The winter physical habitat (label 'winter' on Figure 8) for trout is much less than the habitat the rest of the year because the velocity criteria for the physical habitat requires a lower velocity for the same level of suitability. The winter habitat criteria used in the calculation of the winter habitat relation in Figure 8 were developed for a study of the Gunnison River to the north of the Animas River watershed reported by Nehring and Miller (1987). The other trout criteria were modified for the Animas River study from criteria developed for the Salmon River in New York (Culp and Homa, 1991). The relation in Figure 8 labeled 'win w/ shelters' (an alternative winter habitat relation) will be explained in the section on winter habitat.

There are two periods causing habitat stress on trout in that the physical habitat conditions are not optimal; one of these is the high flow period during spring runoff and the second is the winter period. Both of these will be discussed in the sections below. Water quality can be limiting and a time series model of the water quality limiting factors will be present in a section as part of the fourth observation.

Spring Snow-melt Habitat

The relation for Animas River trout becomes zero at 702 cfs. The model used to develop the relation does not adequately account for velocity hiding places in the stream channel. The trout habitat stress index in Figure 9 is intended to show the years that may limit trout populations because of period of adverse velocity habitat. The equation used to calculate a Trout Habitat Fish Stress Index (THSI) is $THSI = \sum((Q-702.0)/100)$ and the summation is over a water year. Because the critical discharge is 702 (below which the habitat stress is zero) the summation is effectively over the spring runoff period. The assumption is that the velocities will inhibit fish growth and survival during the spring runoff period if the THSI is larger than zero. Additional details about the trout habitat stress index are presented in Milhous (1999).

Winter Habitat Analysis

The winter streamflows are small relative to the annual discharge. The river is habitat for trout in reaches where the water quality does not limit the fish populations. Analysis in a previous paper (Milhous, 2002) showed that winter habitat conditions are limiting for trout populations if velocities and depths are the only habitat variables considered but if the size of the substrate is added to the physical habitat then there is winter habitat for certain sizes of fish. Analysis of the substrate sizes in the upper river shows the range of the sizes of the rocks on the surface (armour) may provide reasonable winter habitat for trout but that the expected trout species would be the smaller species (for example brook trout). Brook trout are found in the upper river.

The distribution of the sizes of the armour at four locations in the reach of river that we are interested in is shown in Figure 10. The reach upstream of Howardsville is relatively flat and the reach downstream relatively steep. The site used in the simulation of the physical habitat is probably reasonably representative of the reach as a whole. An assumption at this point is that the particle sizes are a good way of estimating the size of the hiding places in the surface. For that reason an average of the percentage of the surface armour is used as a weight for the percentage of the surface with hiding from winter 'high' velocities. The size needed was assumed to be at least 10 cm (based on the HEP criteria, Raleigh, 1982). The percentage of each sample less than 10 cm was 39.8, 66.2, 100.0, and 10.5 for an average of 54.1 % for

the reach. This means that 45.9% of the reach has adequate substrate and the reach suitability weight for the substrate is 0.459.

The two sets of winter habitat versus discharge relations are shown in Figure 8 ('winter' and 'win w/ shelters'). The 'winter' relation is based on the fish not having places to hide from the velocities in the stream. The velocity hiding relation assumes that fish can find a place to hide if the velocities are less than 4.1 cfs and the habitat is weighted 1.0 for velocities less than 4.0 cfs. The substrate weight was 0.459 obtained from the armour size distribution shown in Figure 10 and discussed above.

A winter habitat time series analysis was done using winter streamflows of the minimum average 10-day discharge in the winter which was assumed to be between 1 December and 28 February of each water year. The velocity hiding relation from Figure 8 was used as the physical habitat function needed to transform the streamflows to the annual winter habitat time series presented in Figure 11. There is not much variation in the winter habitat from year to year.

Two trout species (brown and brook) spawn in the fall and the eggs incubate during the winter. The fall stream flows are higher than in the winter which means there can be a loss of eggs because of de-watering of redds as has been observed in the Gunnison River (Nehring and Miller, 1987). An index to the spawning habitat loss was calculated using a discharge versus width function based on the USGS discharge measurement summaries. The spawning habitat loss is the percent width reduction calculated as the difference in the width during the spawning period in October and the minimum width between 1 December to 28 February period (or 0 if there is not a reduction in width) divided by the width in October. The October spawning width is assumed to be the width at the average discharge for October. The minimum width between 1 December – 28 February is assumed to be the minimum width that incubates during the winter. The spawning habitat loss for each water year is shown in Figure 12. The spawning habitat loss is sometimes significant (between 20 and 30%) and other times maybe not as significant (5 to 10%). The working assumption behind the index is that redds are uniformly distributed across the width. This is probably not true and the index will underestimate the loss if the redds are near the edge in October and overestimate the loss if the redds are in the channel bottom. For the upper Animas River the loss is probably underestimated.

The fry for fall spawning fish will emerge in the spring when the velocities may not be optimal. In the Animas River the fall spawning fish are brown and brook trout. The assumption is made that the fry habitat of importance is between 16 April and 15 July. It is also assumed the discharge to consider in calculating the fry habitat for each year is the maximum average discharge for a seven day period between 16 April and 15 July. The annual fry habitat for fall spawning fish is shown in this slide. The simulated annual habitat available to the fry of fall spawning fish is given in Figure 13.

The fry for spring spawning fish will emerge in the summer when the velocities may be closer to optimal (compared to fall spawning fish). In the Animas River the spring spawning fish are rainbow and cutthroat trout. The assumption is made that the fry habitat of importance is between 1 July and 31 August. It is also assumed the discharge to consider in calculating the fry habitat for each year is the maximum average discharge for a seven day period between 1 July and 31 August. The annual fry habitat for spring spawning fish is shown in Figure 14.

From the winter habitat time series analysis, an observation is that the hydraulic and hydrologic environment favors spring spawning fish. This is especially true when we consider the fry habitat conditions shown in Figures 13 and 14. From the trout habitat stress analysis it was learned there are spring conditions that may limit the numbers of trout found in the upper Animas River.

Observation 4. The simulation of habitat suitability with metals transport in the river.

Annual variation of metals habitat suitability could be part of an analysis of the suitability of a river for trout if the metals concentrations are considered to be high. An approach to a time series of trout habitat suitability is presented below. The work is preliminary and will change with further investigation. The present objective is to show that metals impacted habitat time series analysis can (and probably should) be done when metals concentrations are high.

The variation of the metals concentrations can have a significant impact on the actual ability of aquatic animals to use the physical habitat. The variation of the concentration of zinc in the Animas River below Silverton is presented in Figure 15. The vertical lines represent boundaries between different levels of movement of the bed-material. The left most vertical line (at 279 cfs with a dimensionless shear stress of 0.009) divides a very stable streambed from a streambed with a rather small amount of movement. At 602 cfs (a dimensionless shear stress of 0.021) the relatively stable streambed becomes a bed with increasingly significant movement. At 958 cfs (dimensionless shear stress of 0.035) the streambed has a high portion of the bed-surface in motion. At 1680 cfs (dimensionless shear stress of 0.084) about (90% of the stream-bed is in motion and there is general bed material transport.

In Figure 15 it would seem that for discharges less than 279 cfs, the zinc concentration is not related to discharge. In Figure 16 the evidence is that the zinc concentrations following spring runoff are related to the time following the major fraction of the runoff.

The model used to simulate daily zinc concentrations has two components. The first component is when the discharge is larger than 270 cfs the zinc concentration is 300 µg/l except for the first four days following the winter low flows. For the first four days following winter and when the discharge exceeds 550 cfs, the concentration is 500.0 µg/l. The second component is for discharges less than 270 cfs. For a discharge less than 270 cfs the relation used is zinc concentration (in µg/l) = $300.00 + 1.5625 * \text{day}$, where day is the number of days after the end of June. The reason for a higher concentration of zinc the first four days when the discharge exceeds 550 cfs following winter is that 550 cfs is the discharge at which the streambed is starting to be moved by the flowing water. This means the streambed is flushed of stored zinc. An alternative explanation is that at a discharge of about 550 cfs, the watershed is flushed of water that has had a relatively long time in contact with the rocks. The average annual zinc concentrations generated using this model is presented in Figure 17.

A habitat suitability function for cutthroat trout is presented in Figure 18. The cutthroat suitability curve was developed for zinc from three sources. The first is a paper by Woodward et al (1997) that reports cutthroat trout will avoid, if they can, waters with a concentration over 28 µg/l in the Coeur d'Alene basin in Idaho. The assumption in Figure 18 is that the chronic limit for cutthroat was the same as for rainbow trout and information in Besser and Leib (1999) can be used; the acute limit is

from Besser and Leib (1999). Woodward et al (1997) indicate that avoidance of metals contaminated habitats by cutthroat trout may cause a reduction in fish populations. In other words, trout populations can be reduced when zinc concentrations are well below toxic concentrations. A similar relation was developed for brook trout using judgment and information in Besser and Leib (1999).

The zinc concentrations in Figure 17 were combined with the suitability relation in Figure 18 to give a time series for zinc habitat suitability presented in Figure 19. The annual values of the zinc suitability are presented in Figure 20 for both cutthroat and brook trout. Rainbow trout would have similar values to cutthroat trout and brown trout similar values to brook trout. The minimum daily value during a water year of the suitability was used as the annual values of the suitability. This minimum habitat suitability occurred between 23 April and 12 May for the 9 years of record used in the analysis.

From the zinc habitat analysis it demonstrated (observed) that annual values of a river can be calculated of the habitat suitability considering the zinc concentrations. The most difficult part is the development of a model to calculate the daily zinc concentrations.

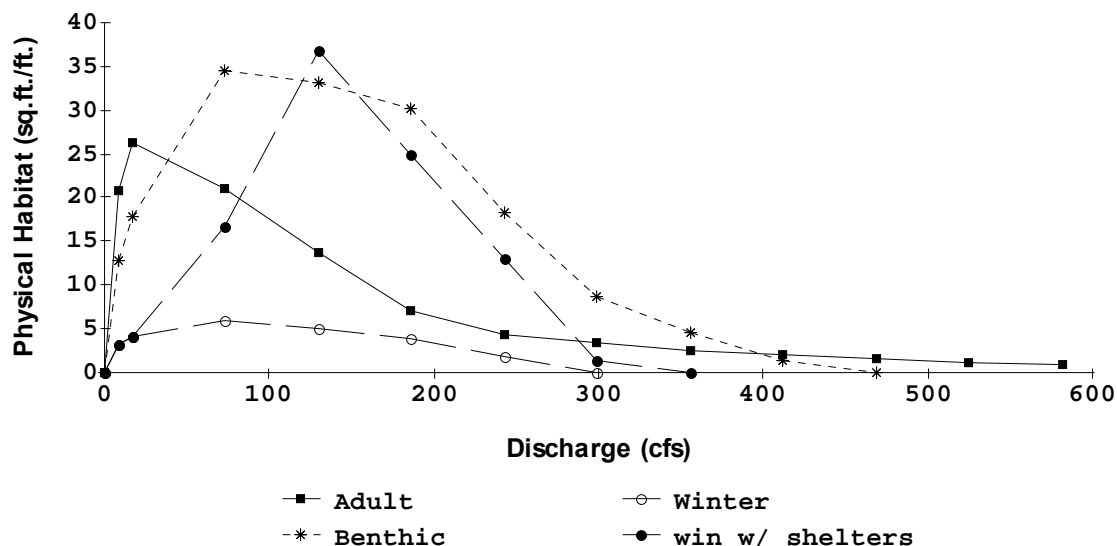


Figure 8. Physical habitat as a function of discharge for the Animas River at Howardsville. The HABVD program in PHABSIM was used to generate the relations. The win w/ shelters (winter habitat with velocity shelters) relation includes the size of the surface armour in the generation of the physical habitat.

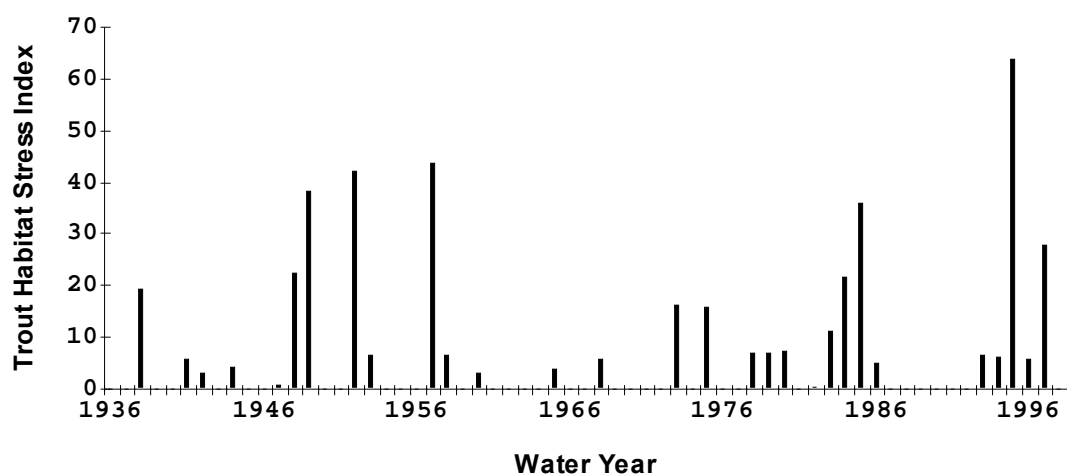


Figure 9. Annual spring runoff trout habitat stress index for the Animas River at Howardsville. A positive value of the index means the velocities exceed the upper limit of the velocity criteria.

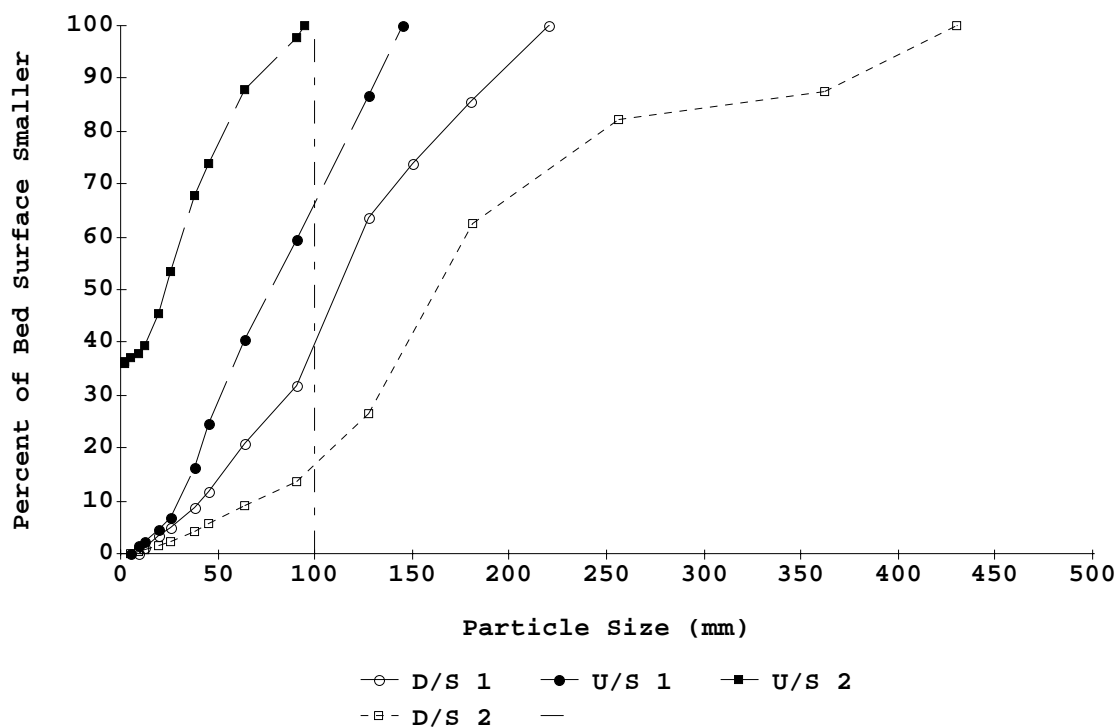


Figure 10. Surface (armour) bed-material of the Animas River near Howardsville. Two sample locations are downstream (D/S) of Howardsville, and two are upstream (U/S).

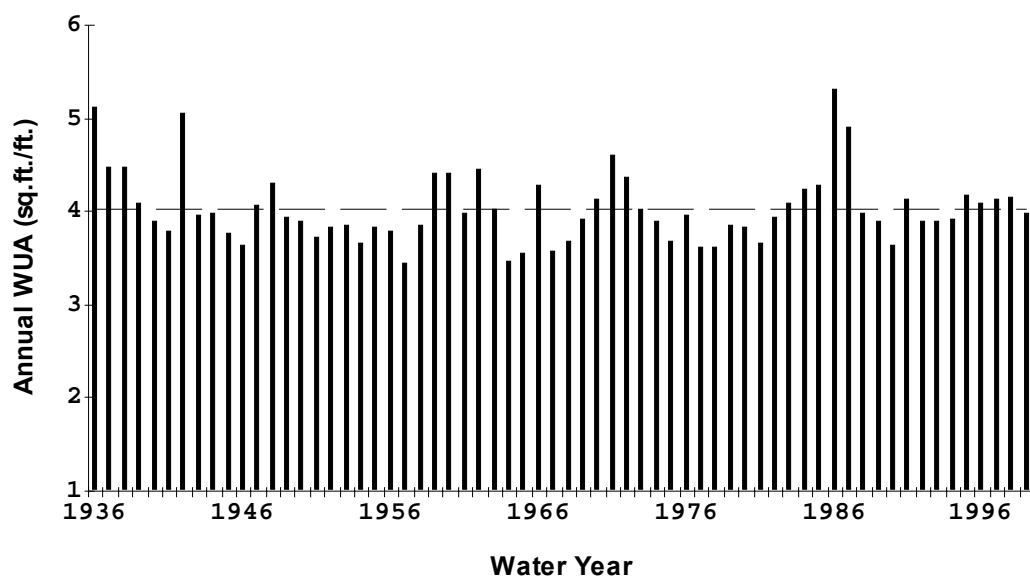


Figure 11. Annual winter habitat in the Animas River at Howardsville, Colorado. The habitat was calculated using the Physical Habitat Simulation System.

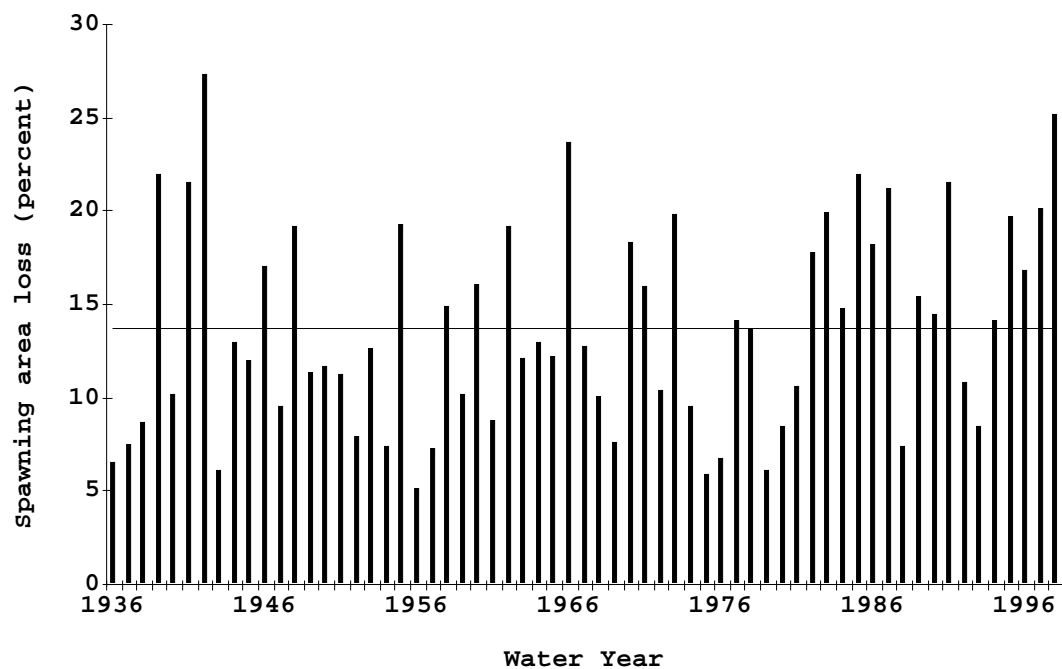


Figure 12. Percent of fall spawning area lost by de-watering between time of spawning and the time of emergence of the fry from the gravels. Calculated using streamflow and cross section data for the Animas River at Howardsville

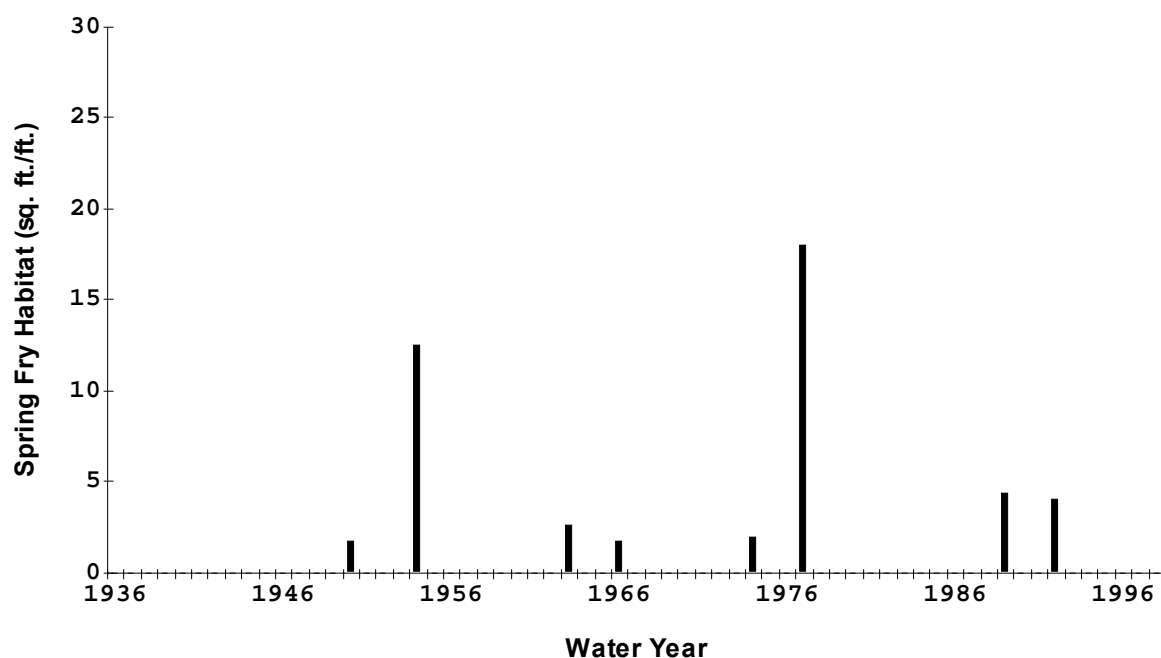


Figure 13. Annual spring fry habitat available based on data for the Animas River at Howardsville. Spring fry habitat is the habitat available to trout fry emerging after incubation in the winter (fall spawning).

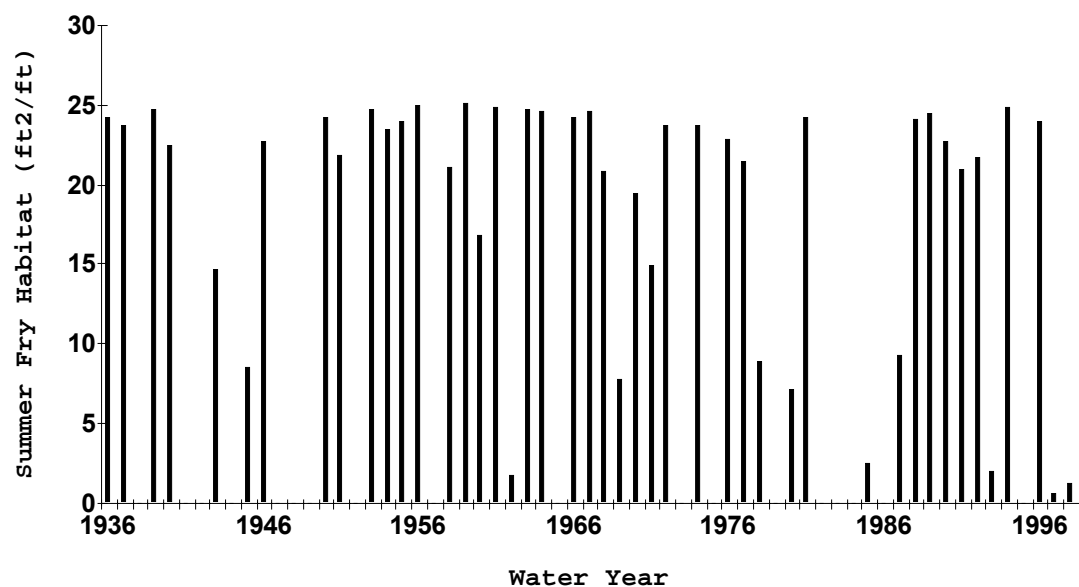


Figure 14. Annual summer fry habitat available based on data for the Animas River at Howardsville. Summer fry habitat is the habitat available to trout fry emerging after incubation in during the sprint and early summer.

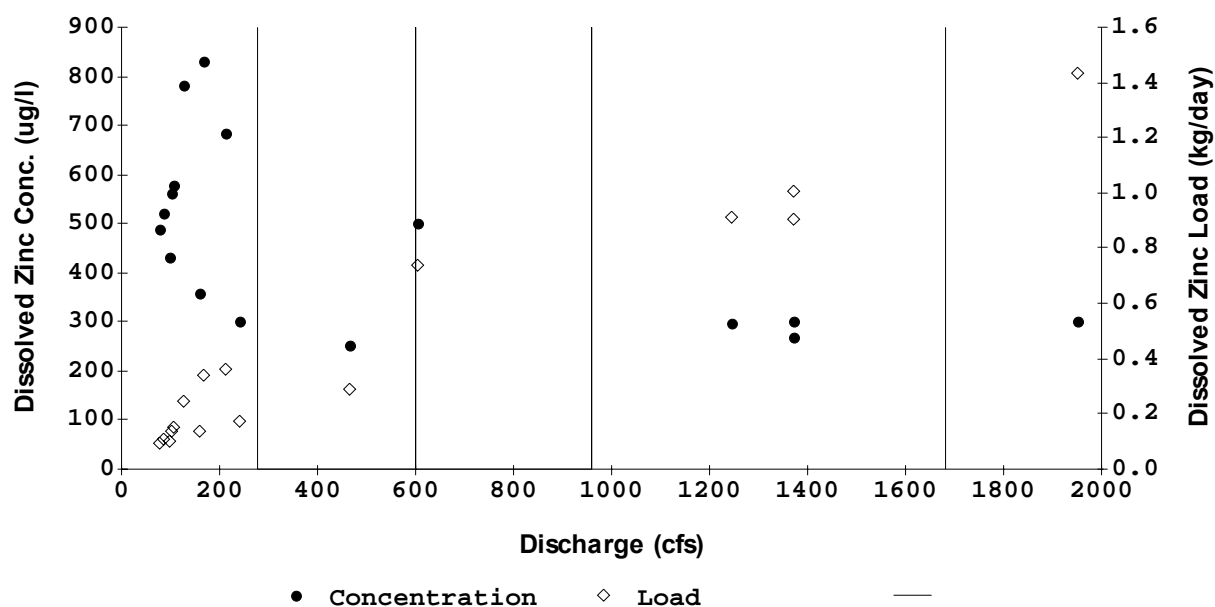


Figure 15. Discharge versus dissolved zinc concentrations for the Animas River below Silverton. The vertical lines divided the discharges into 'cell' of different bed-material movement capability of the river.

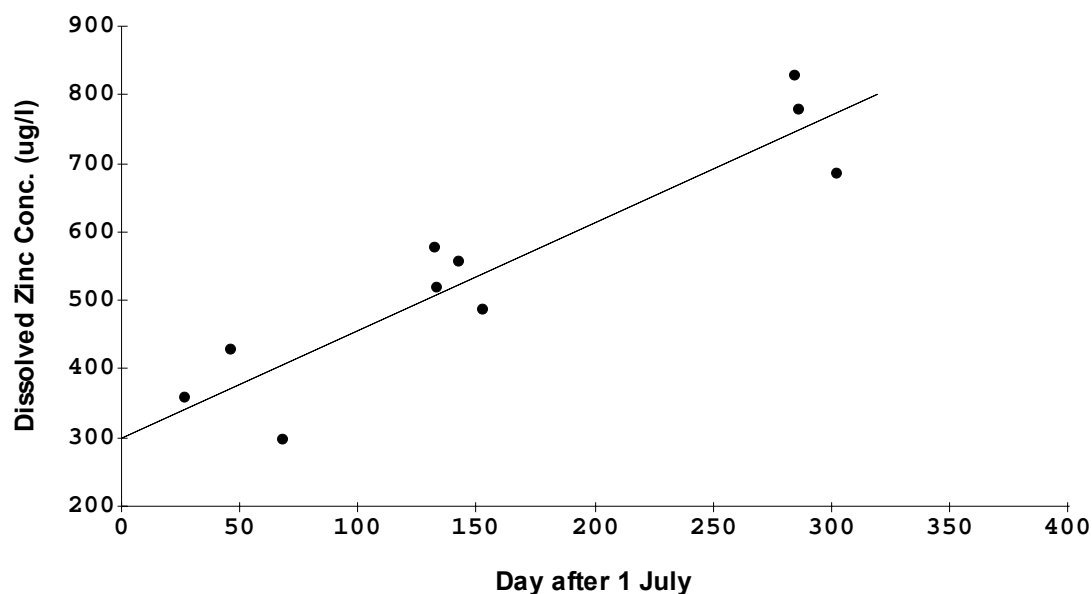


Figure 16. The relation between the number of days after the spring runoff (1 July) and the zinc concentration.

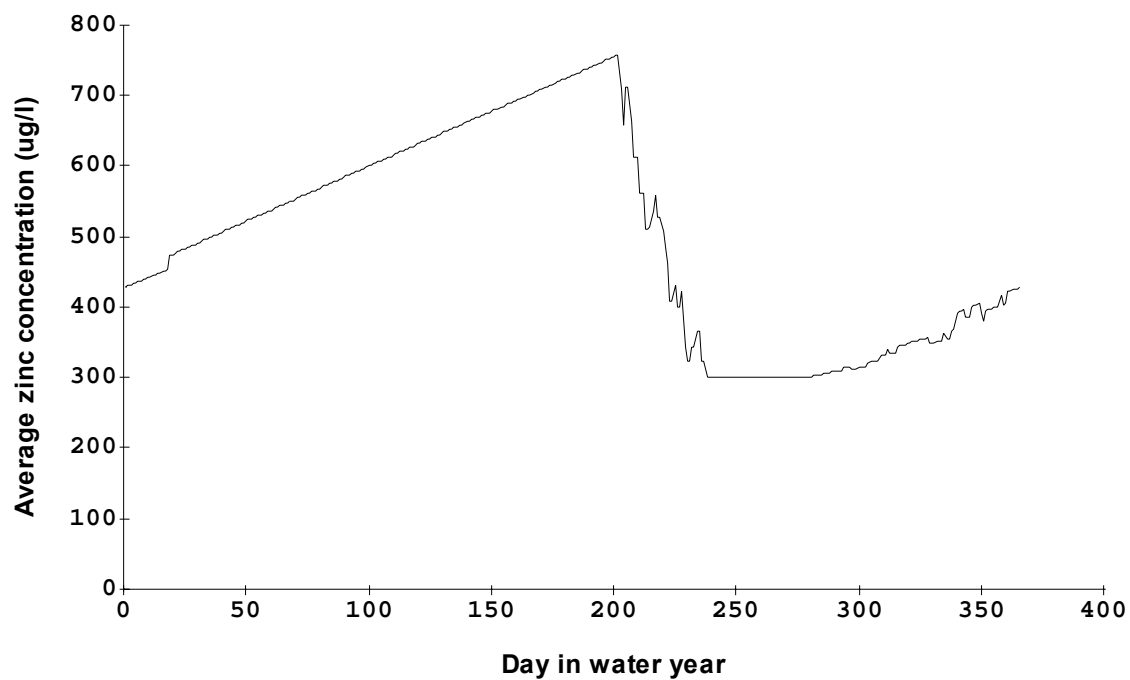


Figure 17. The average daily zinc concentration simulated for the Animas River below Silverton.

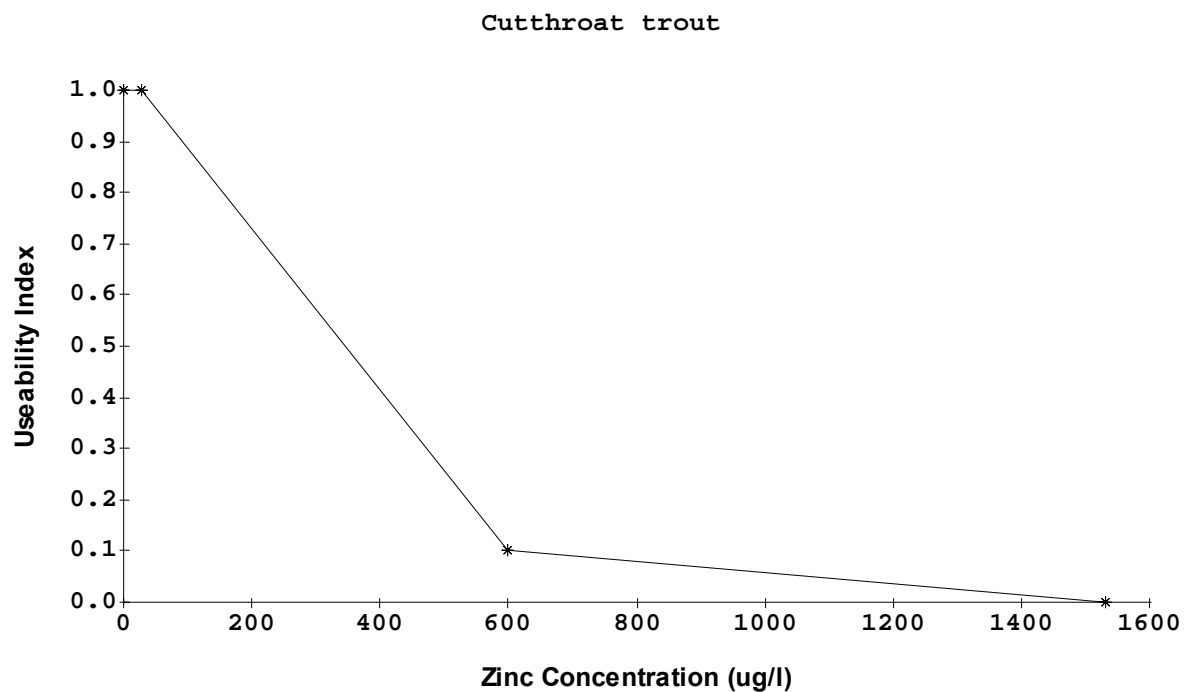


Figure 18. Cutthroat trout habitat suitability function for zinc concentrations.

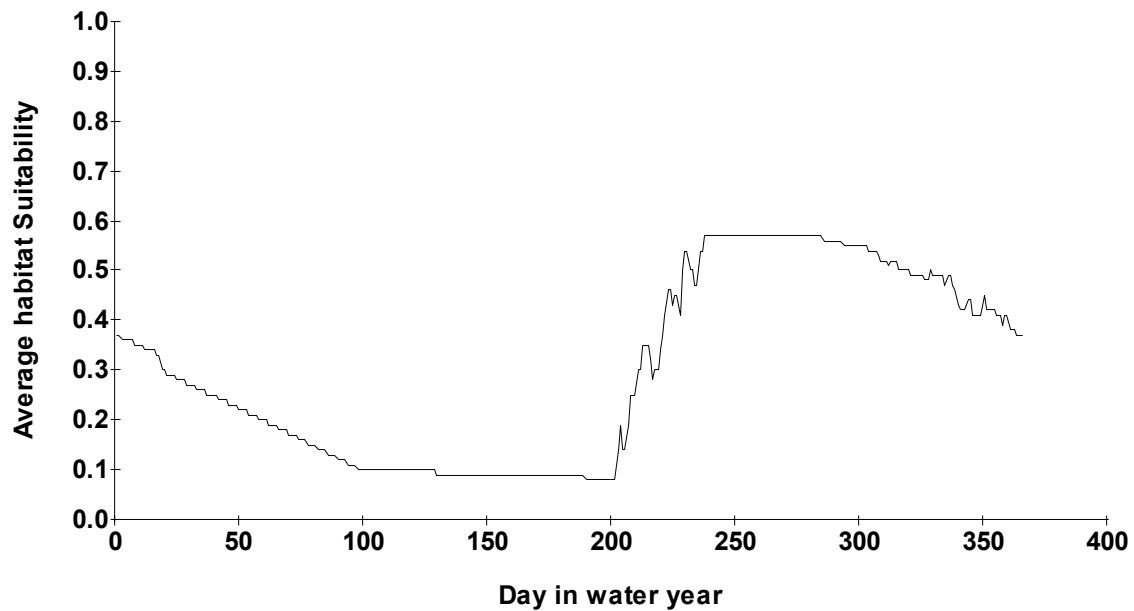


Figure 19. Daily average cutthroat trout habitat suitability calculated from simulated zinc concentrations in the Animas River below Silverton.

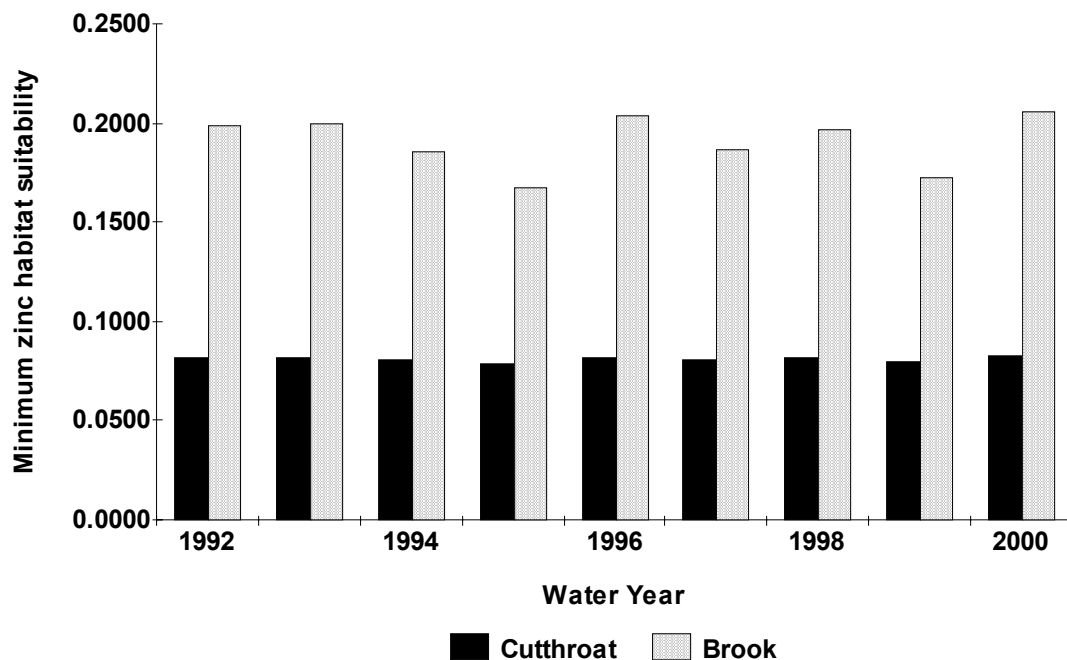


Figure 20. Annual zinc habitat suitability for cutthroat and brook trout in the Animas River below Silverton. The annual habitat is the minimum of the daily habitat suitability values in a water year.

Discussion

The Virgin River channel change observation (first observation) is the importance of keeping the three sets of data as individual data sets. There is also a secondary observation. There was significant difference in the high and low data set time series in Figure 6. The problem is that the differences of the high and low compared to the middle data set relation may be a result of the habitat calculated for a discharge of 1000 cfs. The secondary observation for this suspected upturn in the calculated habitat is that there might be problems with the model being used (in this case PHABSIM) when a transitional channel is being analyzed.

The substrate for the three data sets changed significantly between the three data sets. The second observation is that the channel index is not fixed (the usual assumption) in a river with a moveable-bed and the changes can be significant and important to an understanding of the aquatic system. In the paragraph above a statement about a 'transitional channel' was made. It is possible that the middle discharge data set is the stable data set. In Figure 3 the middle discharge profile is below the low and high discharge data sets; also, there is more gravel in the channel for the middle discharge data set (Figure 7) and the river is mostly sand-bed for the high and low data sets. It is probable a sand wave was deposited in the channel and passed through the channel during times of the high and low discharge measurements but was gone by the time of the middle discharge measurement. A sand wave is probable in years with a high Sediment Transport Capacity Index (Figure 5) but as a transitional feature. A moveable bed model may be needed to resolve questions about both the increase in the habitat increase at 1000 cfs for the low and middle discharge data sets and the impact of sand waves on the habitat.

The Animas River is a river with a wide range of streamflows and considerable metals toxicity. Both winter and spring discharges may limit trout populations along with metals toxicity. The third observation (first observation from the Animas River case study) is that habitat time series analysis should be done with a model that specifically links the physical habitat relations and the streamflows and quantifies the limiting factor(s). In the case of winter flows the model is a physical habitat model that includes armour size of the streambed as a habitat factor. For high streamflows (spring runoff), the model is a representation of the time and magnitude the high flows are larger than the highest discharge with acceptable velocities. The high discharge model suggests an improved approach to habitat criteria is probably need.

The fourth observation is that a time series of habitat suitability considering metals toxicity can be calculated. The third and fourth observations show that the hydraulic and streamflow conditions may favor different fish than the metals toxicity conditions. In the Animas River the hydraulic and streamflow conditions favor spring spawning fish. The habitat suitability for zinc concentrations would be better for brook and brown trout (fall spawning fish) than for cutthroat and rainbow trout (spring spawning fish). The secondary observation is that the hydraulic and stream flow conditions may not be best for the same species as favored by the water quality conditions.

The Animas River case study illustrates a concern about habitat analysis. The criteria developed for use in PHABSIM most often is intended to show the physical conditions desired by an aquatic animal. This was the case for the relations in Figure 11 except for the winter habitat with velocity shelters relation. The 'win w/ shelters' relation was developed to show that for winter conditions when optimal habitat was not

available (or very small) there could still be survival habitat. The same type (survival) analysis could have been done for high flows but instead a habitat stress index analysis was done instead – the assumption was that the some of the fish would probably survive but with reduced numbers if the high flow habitat stress index was large (Figure 9). Taken together, the idea is that normal PHABSIM analysis may give good results for most of the year but it would be a good idea to consider how fish (and other aquatic animals) survive in adverse flow conditions when the desirable habitat conditions approach low values. The cutthroat trout zinc suitability relation illustrates a similar idea. Cutthroat trout will avoid, if they can, waters with a zinc concentration over 28 µg/l. The toxic limits are much higher. What happens if the concentration is over 28 µg/l? Is this a survival situation? It is possible that in environmental flow analysis, both desirable and survival flow analysis should be done. In other words, when a time series of habitat is done using a physical habitat versus discharge relation and the habitat is zero, the analysis should than include some information on the ability of the aquatic animal to survive zero desirable habitat. It is possible the length of time the zero desirable habitat, but with survival habitat greater than zero, occurs will play a crucial role in the environmental flow analysis.

References

- Besser, J.M. and K.J. Leib, 1999.** Modeling Frequency of Occurrence of Toxic Concentrations of Zinc and Copper in the Upper Animas River. Pages 75-81 in D.W. Morganwalp and H.T. Buxton, editors. U.S. Geological Survey Toxic Substances Hydrology Program–Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12. Volume 1 of 3 – Contamination from Hard-Rock Mining. *USGS Water-Resources Investigations Report 99-4018A*. U.S. Geological Survey, Reston, Virginia USA.
- Culp, T.R. and J. Homa, Jr., 1991.** Fish and Macroinvertebrate Habitat Suitability Index Curves. Report to Niagara Mohawk Power Corporation. Ichthyological Associates. Lansing, New York.
- Karr, J.R. 1991.** Biological Integrity: A Long-Neglected Aspect of Water Resources Management. *Ecological Applications*, 1(1): 66-84.
- Meyer, K.A. and J.S. Griffith, 1997.** Effects of Cobble-Boulder Substrate on Winter Residency of Juvenile Rainbow Trout. *North American Journal of Fisheries Management*, 17:77-84.
- Milhous, R.T. 1995.** Changes in sediment transport capacity in the Lower Gunnison River, Colorado, USA. Pages: 275-280 in G. Petts (Ed.) *Man's Influence on Freshwater Ecosystems and Water Use*. IAHS Publication 230.
- Milhous, R.T. 1999.** Aquatic Physical Habitat and Hydrology in Abandoned Mine Land Studies. Pages: 47-54 in D.W. Morganwalp and H.T. Buxton (Eds.) *U.S. Geological Survey Toxic Substances Hydrology Program – Proceedings of the Technical Meeting*, Charleston, South Carolina, March 8-12. Volume 1 of 3 – Contamination from Hard-Rock Mining. *USGS Water-Resources Investigations Report 99-4018A*.

- Milhous, R.T. 2002.** On Trout Winter Habitat in the Animas Basin. Pages: 191-202 in J.A. Ramirez (Ed.) *Proceedings of the Twenty Second Annual American Geophysical Union HYDROLOGY DAYS*. Hydrology Days Publications. Colorado State University, Fort Collins, Colorado USA. .
- Milhous, R.T., M.A. Updike, and D.M. Schneider, 1989.** Physical Habitat Simulation System Reference Manual-Version II. Instream Flow Information Paper No. 26. *U.S. Fish and Wildlife Service. Biological Report 89(16)*. Washington, DC USA
- Milhous, R.T., J.M. Bartholow, M.A. Updike, and A.R. Moos, 1990.** Reference Manual for Generation and Analysis of Habitat Time Series - Version II. *Instream Flow Information Paper No. 27. U.S. Fish and Wildlife Service. Biological Report 90(16)*. Washington, DC USA.
- Nehring, R. B. and D. D. Miller, 1987.** The Influence of Spring Discharge Levels on Rainbow and Brown Trout Recruitment and Survival, Black Canyon of the Gunnison River, Colorado. In *Proceedings of the Annual Conference of the Western Association of Fish and Wildlife Agencies*, July 13-15, 1987. Salt Lake City, Utah USA.
- Raleigh, R.F. 1982.** Habitat Suitability Index Models: Brook Trout. *U.S. Fish and Wildlife Service. Report FWS/OBS-82/10.24*. Washington, DC USA
- Raleigh, R.F, T. Hickman, R.C. Solomon, and P.C. Nelson, 1982.** Habitat Suitability Index Models: Rainbow Trout. *U.S. Fish and Wildlife Service. Report FWS/OBS-82/10.6*. Washington, DC USA.
- Raleigh, R.F., L.D. Zuckerman, and P.C. Nelson, 1986.** Habitat Suitability Index Models: Brown Trout. *U.S. Fish and Wildlife Service. Biological Report 82(10.124)*. Washington, DC USA.
- Woodward, D.F., J.N. Goldstein, and A.M. Farag, 1997.** Cutthroat Trout Avoidance of Metals and Conditions Characteristics of a Mining Waste Site: Coeur d'Alene River, Idaho. *Transactions of the American Fisheries Society*, 126:699-706.